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ABSTRACT

This report summarizes the results obtained and the work performed during the first nine months of an eighteen month program to develop a new ultra dense optical mass storage memory system based on spectral hole burning (SHB) media. The goals of this particular program were to (1) investigate the fundamental properties of a "Frequency Channel" concept which holds promise for enhancing the resistance to erasure of data recorded in SHB media; (2) investigate the fundamental and practical aspects of the data erasure in SHB media; and (3) to build and test a laboratory demonstration system which has all the key characteristics vital to the operation of this memory system as a digital computer memory system. The experimental aspects of the program have been found to be most efficiently performed by addressing all of the above tasks in parallel, so at present the results obtained are preliminary. The work is progressing well and is expected to be completed on time. We also wish to report on the added result that a new concept for a high performance content addressable memory system (CAM) has been developed and will be described in the report which follows.

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1 Introduction

This program is the second phase of an SBIR program to investigate the fundamental and practical aspects of developing an ultradense optical memory system based upon SHB media. These media have the unique demonstrated property of being able to record information via photo-bleaching while being very selective in the wavelength of the light used to record the information. Small changes in the wavelength of the laser light used for exposure (as small as 100 MHz) can allow for the independent recording of new data. This flexibility in data storage means that information can be recorded as a function of the three spatial dimensions (x,y and z) as well as a function of laser wavelength (which we can realistically describe as a fourth dimension). This added dimensionality permits us to address much more of the fundamental capacity of the recording medium.

Volume storage can make use of a very large number of recording centers. For example, a typical host medium can be doped to a level of 10^{19} recording centers per cm^3. Achieving a fundamental signal to noise of 30 will require approximately 10^3 recording centers per bit. If we allow a factor of 10 for a "guard band", then the fundamental capacity of a 1 cm cube is about 10^{15} bits.

Accessing this capacity throughout the entire volume of a 1 cm cube can be a problem using conventional "bit" (or image) storage techniques. A lens with a numerical aperture of 0.5 (about equal to a high quality microscope objective) can address a volume of about 25 μm^3. In a cubic centimeter there are then approximately $4 \times 10^{10}/cm^3$ independently addressable regions (bits). Even conventional holographic techniques are found to be limited to a similar capacity due to practical considerations of system design. How can we address the much larger storage capacity discussed above?

SHB materials provide an additional dimension for addressing recording centers. The inhomogeneous absorption spectrum is made up of a large number of homogeneously-broadened absorption lines. At low temperatures, the absorbing centers within a single homogeneously-broadened linewidth can be addressed independently of any other population of recording centers. This allows data to be recorded at one wavelength which cannot be seen by any other wavelength. **The additional recording dimension provided by laser frequency provides a means to access recording centers independently at a much finer scale than an optical wavelength.** Materials are available which can provide 10^4 to 10^5 independent recording frequencies. This large frequency diversity effectively multiplies the potential capacity from $4 \times 10^{10} cm^3$ to as much as $4 \times 10^{15} cm^3$ bits permitting "access" to the material's fundamental capacity. This enormous fundamental capacity permits us to anticipate that "conservatively designed" memory systems having capacities of 10^{12} bits and greater are feasible based upon these materials.

1.1 The Memory System

The proposed memory system has an inherently parallel architecture as shown in Figure 1. (A patent concerning this memory system architecture has received a "Notice of Allowance" and is held by SPARTA Inc.[1]) The data is recorded as holograms in a page-oriented digital format. Because of the holographic method of recording, the full volume of the recording medium can be utilized over thicknesses which range up to 1 cm. By also recording information as a function of discrete laser frequencies via the tunable laser and the unique capabilities of the SHB materials, one is able to multiply the storage capacity of the architecture even further. The net result is a

system which is compact in format, permits massively parallel rapid access, and has enormous storage capacity.

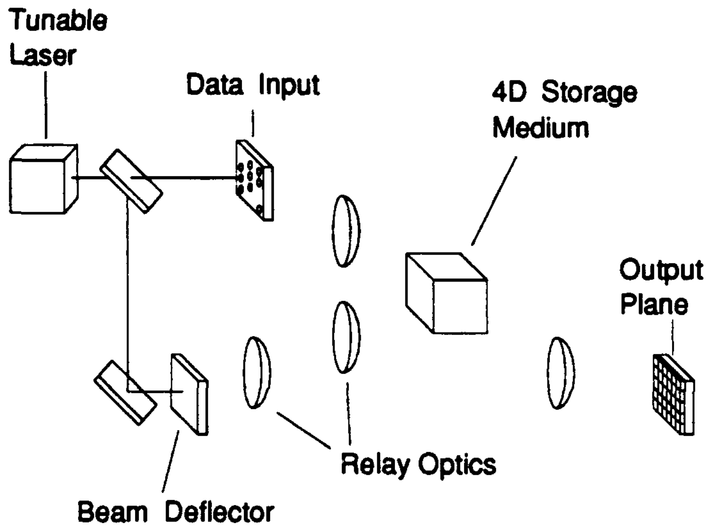

Figure 1. Schematic diagram of the proposed optical memory system.

1.2 Spectral Hole Burning and Frequency Channels

The concept of spectral hole burning (SHB) is best understood on the molecular level. A single molecule has a set of energy levels between which transitions are allowed. If the energy of the photon approximately matches one of the transition energies required, the photon can be absorbed by the molecule. If, upon absorption, a chemical change to the molecule is induced, the absorption levels of the new molecule will not match the old ones. Therefore, the new molecule will not absorb light at the frequency of the first photon. In this way, the absorption at a specific frequency can be modulated, permitting the recording of information. If an absorbing molecule is contained within an amorphous or glassy host, the specific absorption frequency for each molecule can be different, determined by its local environment. One then finds that small subpopulations of molecules can be selectively modulated by choosing the photon frequency. Utilizing the full range of frequency available can provide an enormous potential storage capacity when coupled with the three spatial dimensions.

SPARTA has conceived a unique scheme which allows the recording of refractive index holograms in SHB materials which have been considered conventionally only in terms of absorptive effects. The proposed approach creates regions of frequency space (channels) which are bleached by a narrow linewidth tunable laser. Phase holograms are then recorded near the absorption edge where the refractive index modulation is appreciable. There the real component is modulated by the molecular population present in the adjacent absorptive structure (see Figure 2). The high molecular population within the absorption structure provides a large reservoir of potential storage capacity. The transparent channels effectively provide "access channels" to the vast storage capacity of the SHB material. The reason the Frequency Channel approach provides a significant advantage is that the material can be very heavily doped, providing many more recording centers for data storage. The refractive index modulation present within the

bleached channels is adequate to allow the storage of many high efficiency phase holograms, and many of these channels can be contained within the frequency range of the SHB material.

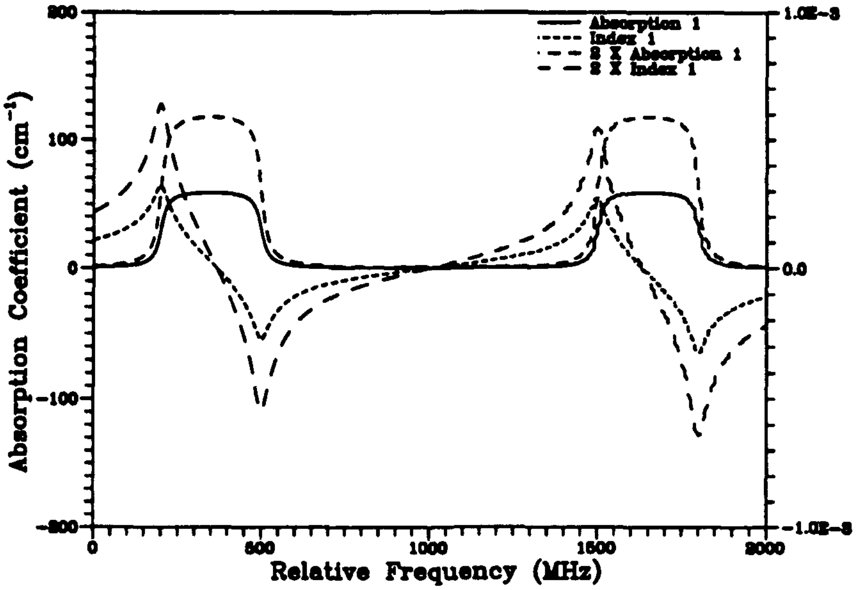

Figure 2. Computer simulation of two adjacent absorption structures showing the modulation of the resultant refractive index. Such a structure is possible with porphine in polyethylene at 4 K.

By potentially providing storage densities as high as 10^{12} bits/cm^3 of material, useful memories of enormous capacity could be extremely compact and also operate with very low power consumption. Because of the intrinsically parallel manner of holographic reading and writing of data the potential data rate is extremely high.

1.3 Advantages to this Approach

The anticipated benefits of a high capacity optical memory based on the frequency channel structure in SHB materials rest upon the following key attributes.

1. High data rates are inherently available in the proposed holographic memory system architecture because of its parallel structure.
2. The holographic approach permits use of **available** SHB materials. Therefore, system development can be initiated without further materials research.
3. Phase holograms in SHB materials have distinct advantages.
4. Frequency Channels provide access to the fundamental capacity of the material.
5. Enhanced control of the writing and erasure process is provided by the Frequency Channel structure.
6. The system architecture (complete with cryostat) is extremely compact.

1.4 Program Overview

The principal goals of this experimental program can be summarized as addressing (1) Frequency Channels (2) Erasure and (3) Assembly and Test of a Demonstration system. A key feature of our experimental approach is to utilize the optical and electronic system to both construct the demonstration system as well as to provide platform from which to carry out the experiments in frequency channels and erasure. This provides us with a very efficient means for accomplishing all the required tasks, but has the requirement that many of the tasks be carried out in parallel. Because of this much of the work reported on here is with respect to experiment planning and preparation of the experimental system and most of the major tasks are only partially complete. However, we have some interesting results to report as well as a new concept concerning a Content Addressable Memory (CAM) system which we believe holds promise as being a very high performance system for search and retrieval of digitally encoded data.

2 Component Selection for The Demonstration System

Since the demonstration system also provides the platform for most of the experiments which will be performed during the program, a detailed description of this system and the attributes of the components is provided.

2.1 The Tunable Laser

The laser which we selected for this program is a Coherent tunable dye laser which we have modified to permit PC control of the laser wavelength. To simplify our efforts the system is simply tuned by a combination of a birefringent filter and an etalon both of which can be mechanically adjusted by motorized micrometers so as to permit direct access to any desired wavelength. The combination of the etalon and the birefringent filter provide a single laser line which is only 2.5 GHz wide, and can be readily tuned over a 20 nm range continuously. The selected operating wavelength is centered at 650 nm so as to match the center wavelength of the SHB medium which we have selected. Total output power is approximately 200 mW.

2.2 The Cryostat

For our demonstration system, and most of our experiments, we have purchased a liquid helium cryostat from Janis Research. Because of the highly insulating nature of the SHB media, vapor cooling of the medium is a desirable approach (making thermal contact to a polymer medium without imparting excessive stress is difficult). For this type of research application Janis makes a cryostat which cools the sample by immersion in a continuously flowing stream of helium vapor. The benefit of this approach is that the temperature of the sample may be easily maintained over a wide range without imparting any mechanical strain to the sample. One disadvantage is that at 4 to 8 degrees K the flowing helium vapor is sufficiently turbulent to significantly disturb the laser beam which must pass through the cryostat for our experiments. The solution to this problem was a combination of two modifications. The first was to add a pump to the system which reduces the pressure of the helium as it flows past the sample. The addition of the pump has the added advantage of achieving a lower operating temperature for the same helium flow, or the same temperature with less helium flow, making us more efficient. The second modification is to surround the SHB sample with transparent windows which are largely space filling and thereby reduce the optical path length in the turbulent vapor. The combination of these two features has allowed us to record some simple, but quite efficient holograms, having efficiencies as high as 10^{-3} (quite adequate for our tests).

2.3 SHB Medium Selection

The specific SHB medium which we selected is tetrapheny chlorin in polystyrene. We believe that spectral hole burning in this medium has not been reported previously. We selected it for several reasons.

1) Tetraphenyl chlorin (TPC) is one member of a large group of chlorin compounds which have the spectral property of providing a strong single absorption peak in the red (650 nm). This absorption peak represents the more stable configuration of the chlorin ring system. When a spectral hole is burned, the molecular configuration changes and the corresponding spectral absorption shifts also (by 50 nm or more). The spectral shift

is not nearly as large for the porhine based compounds which are of similar nature. This spectral shift property is important for the development of some of our concepts concerning photo-erasure and also for frequency channel creation, and has been seen in the simpler compound Chlorin-I. Our intent was to show that this property is common to more of the chlorin compounds.

2) This chlorin compound is man-made, and inexpensive to synthesize. These attributes will become more important in the future, particularly when issues related to material purity, quality, and availability are addressed.

3 The peak wavelength is 650 nm, a wavelength which is now within reach of laser diode technology and should be useful for future implementation of tunable laser diode systems.

4 The addition of the phenyl groups to the chlorin ring enhance the stability of the ring in its resistance to free radical attack. This is an important property for the preparation of samples in a polymer medium such as polystyrene or PMMA. We have successfully prepared bulk samples of TPC doped PMMA, polystyrene and other alky-PMMA related polymers. In all cases, the TPC was sufficiently stable to permit adequately high doping levels to be achieved.

5) We chose to utilize a polystyrene host for these experiments because we found that samples of very high optical clarity and uniformity could be prepared with simple melt-and-cast procedures. More advanced process are required for PMMA and other similar materials. (This is not a long term limitation since the plastics industry certainly has shown that high optical quality PMMA - a.k.a. Plexiglass - can be prepared in commercial quantities.)

2.4 SHB Media Preparation

While our initial preparations of TPC in polystyrene (PS) samples has been of suitable quality for our initial experiments, we have found that the polystyrene does seem to cause a significant amount of scattering. Close observation indicated that this was particulate or microbubble related and was inherent to the quality of the polystyrene used. The PS used was supplied by Aldrich chemical and had the initial advantage of being easy to melt and cast at low moderate temperatures (150 C).

We also have observed that there was significant scattering from the surface of our cast samples which we have traced to the surface quality of our simple casting mold. Our casting process is rather simple, being a procedure whereby a piece of PS is melted between two microscope slides. We have observed that the level of scattering observed for the resultant PS sample matches that of the glass slide. By comparison, PS samples prepared by melting samples in a simple aluminum weighing dish have a top surface which is not in contact with any solid surface and therefore molecularly smooth (although not flat) exhibiting virtually no surface scattering.

We are presently addressing both scattering sources. A superior quality polystyrene has been obtained from Dupont, which is not specified as being of optical quality, but is often used in optical component manufacturing. We have sampled this material and found it to provide almost negligible bulk scattering while having a slightly higher melting temperature (200 C) than the Aldrich material. The surface scattering problem has been addressed by obtaining high power

laser windows which have very highly polished surfaces and exhibit very low surface scattering levels. We plan to use these laser windows in combination with the Dupont PS to provide SHB samples having very low scattering.

2.5 LCD Selection

Our previous experience has indicated that the quality of the LCD used for inputting coded data into out memory system played a significant role. The standard nematic or supertwist LCD displays exhibit too much cross-talk (or bleeding) between adjacent pixels in a row to provide the independence needed for reliable data encoding. This problem is greatly improved for active matrix LCDs (AMLCD) in which each pixel element is driven by an amplifying transistor. This provides for much greater independence between the pixel elements and allows the display to be operated at a much higher contrast level. As we shall discuss latter, this higher contrast level proved desirable when considering our use of phase coding to enhance our holographic recording efficiency. Other advantages of the active matrix displays are that the commercially available displays have smaller pixels allowing us to input more coded information in each holographic image. The display we have selected is that used in a Sharp XG-1500 video projector which has approximately 89,000 pixels in each of three displays. Each display is approximately 3 inches on the diagonal and our plan is to use the entire display for encoding our computer memory data.

The compromises required for utilization of this inexpensive commercially available display is that we are required to drive the display in standard television video format with our controlling PC. Providing an exact match between the VGA format in our PC and the television format would have required the purchase of an expensive scan converter. To reduce our program costs we have taken the approach of implementing a somewhat complex spacing pattern while encoding the data which provides a suitable match between the VGA format and the LCD projector. The compromise which is required is that only about half of the LCD pixels can be utilized in encoding the data. We believe that this was an acceptable compromise, since total system capacity is not a key goal of this program. As used, this image/data format should permit us to store roughly 3,000 bytes per holographic image.

In the long term, this should pose no problem. For future systems, we anticipate that the displays will be digitally driven, far more compact, and have no relation to the television format.

2.6 CCD Camera

For efficient operation of the memory system with a minimum of supporting computation provided by the PC, the camera selected should provide a close match to the format of the LCD display. The best match would assign 1 camera pixel to each LCD pixel. Registration in the optical system must be good. Once these factors are satisfied, only the minimum amount of camera data needs to be analyzed by the controlling PC to read out the holographically stored data. For our experiments we have also found it convenient to purchase a low cost camera which loads the digitized image file directly into PC memory, reducing PC operation time and programming complexity. For these reasons we have selected the Electrim HR1000 CCD camera.

Only two compromises are required in this selection. There is a small mismatch in the pixel aspect ratios which we have compensated for in our optical design by introducing some

cylindrical optics. The second compromise required is that to properly match the format of the camera to the LCD, only half of the CCD pixels are utilized for reading out data.

2.7 Input Coding

Besides the coding issues already discussed for matching the VGA data format to the television format used in driving the LCD, we have found that two additional aspects of the data coding which are of long term importance are slope coding and phase coding.

Slope coding is also known as error correction modulation (ECM) and is a concept often used in high density magnetic or optical disk memory systems. The principal of operation is that the indication of a 1 or 0 bit is indicated by the local change of the properties of the recording medium, rather than an absolute magnitude of the critical property (for example, magnetic field strength). This permits one to tolerate large area nonuniformities in material properties or system performance, yet maintain a high level of data integrity. Our implementation of this concept is to use two LCD pixels to represent each bit of data. If the first pixel is white and the second black, this represents a 1. If the first is black and the second is white, this represents a 0. This approach permits us to be quite insensitive to illumination nonuniformities as well as any potential recording nonuniformities which may be present. It also has the long term advantage of providing data readout without digitization or thresholding of each pixel, allowing us to achieve very fast readout of the CCD array in high data rate applications at minimal cost. While the penalty for this approach is a 100% usage overhead, it is anticipated that the improvements in recording efficiency, laser light usage, optical system design and superior raw bit error rate are worth it. It also guarantees that the amount of light transmitted by the SLM is a constant, making the consistency of data recording very easy to maintain. In a previous program on a holographic optical memory system [] we have found that this approach provides at least a factor of 100 improvement in the raw bit error rate under the same operating conditions.

Phase coding is a procedure which we have adopted which randomly encodes the phase of the light across the LCD input pattern. The principal reason for this is to add a random high frequency component to the input pattern which distributes the light quite uniformly in the Fourier plane. Since our optical design places the SHB medium at the pupil plane of the optical system, having a uniform distribution of light there prevents "hot spots" in the illumination which can lead to nonlinear recording effects. An alternative approach would be to introduce a diffuser to the input image, but we found that this approach was very wasteful in the laser light usage when high quality imagery was required. By using a phase code which has a maximum modulation frequency matching that of the LCD display, the light is well distributed without being scattered out of the optical system.

Our phase coding approach is implemented by special use of the polarization properties of the LCD display. This can be seen by reference to Figure 3. By selecting an input polarization of the illuminating beam as indicated, the LCD can rotate the plane of polarization for each pixel by a maximum amount. If the output polarizer is oriented to block the light which is rotated by half the maximum amount, then one has a black pixel at this orientation. Efficient transmission is allowed for the input polarization and for the maximum rotated polarization. The net result is that the white pixels can now take on the two potential phases corresponding to a rotated or non rotated orientations. This permits us to scramble the input pattern in phase while permitting us to record contrast patterns which are highly regular. (Highly regular input patterns would provide regular diffraction patterns at the Fourier plane which would again lead to hot

spots and non-linearities.) Once the polarizer is set, the phase code used is created by a simple random number generator, and encoded into the input pattern which is driving the LCD. The price which is paid for this phase coding is to reduce the contrast of the LCD image slightly, but the reduction obtained is considered acceptable.

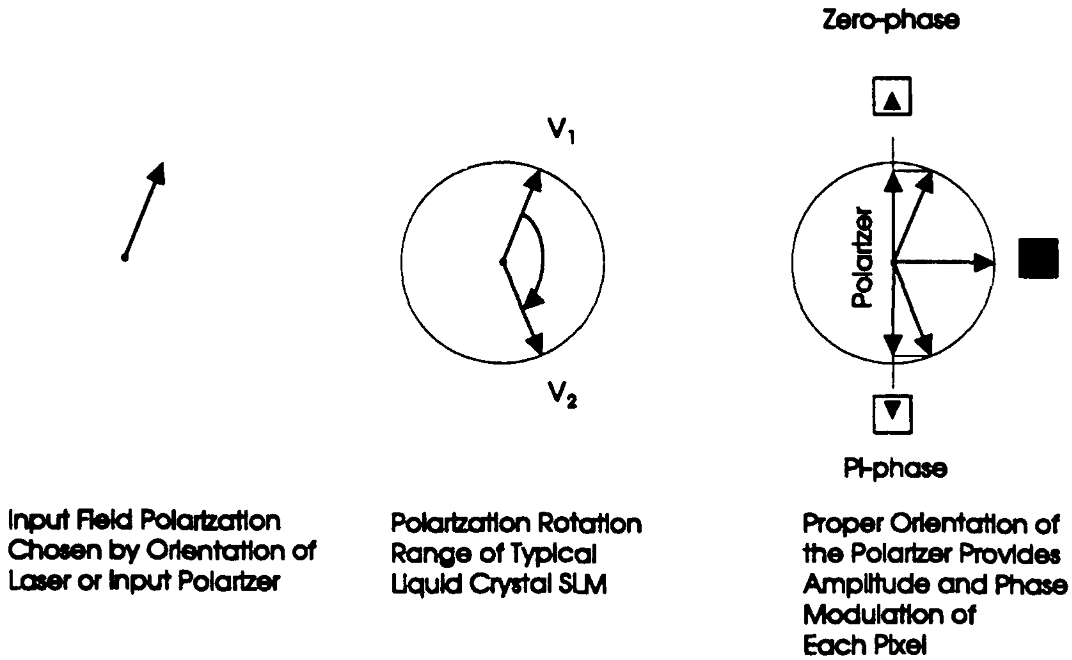

Figure 3. Reorientation of the polarizer associated with a liquid crystal SLM can produce dark pixels or bright pixels with zero or π phase shift.

2.8 Optical Design

The key features required from the optical system are that it is basically an Mach-Zender interferometer with an image plane on one leg as shown in Figure 4. The total length of the optical system is nearly 2 meters, but this length is principally driven by the size of the LCD pixels. Presently these are roughly 160 microns in each dimension, while in the near future we anticipated devices having 10 micron pixels. This change would permit us to greatly reduce the path length in the future by eliminating most of the space required by beam expansion and image reduction.

The system is composed entirely of commercially available, off the shelf, components to keep the costs modest. The optical design is telecentric, to make maximum usage of the light and reduce issues of registration between the LCD and the CCD camera. The LCD image is reduced by a factor of 7.5 and an intermediate image is provided for inspection purposes before reaching the SHB recording medium. A half wave plate and polarizer is used prior to the LCD array to provide the proper input polarization. A polarizer after the LCD is used to properly filter the light before entering the SHB medium. The CCD camera is placed in the imaging beam path, after the SHB medium to record the output holographic image. The image registration with the LCD pattern will permit pixel to pixel correspondence between the LCD and the CCD camera. A slight mismatch in the aspect ratios between the LCD and CCD is easily compensated for

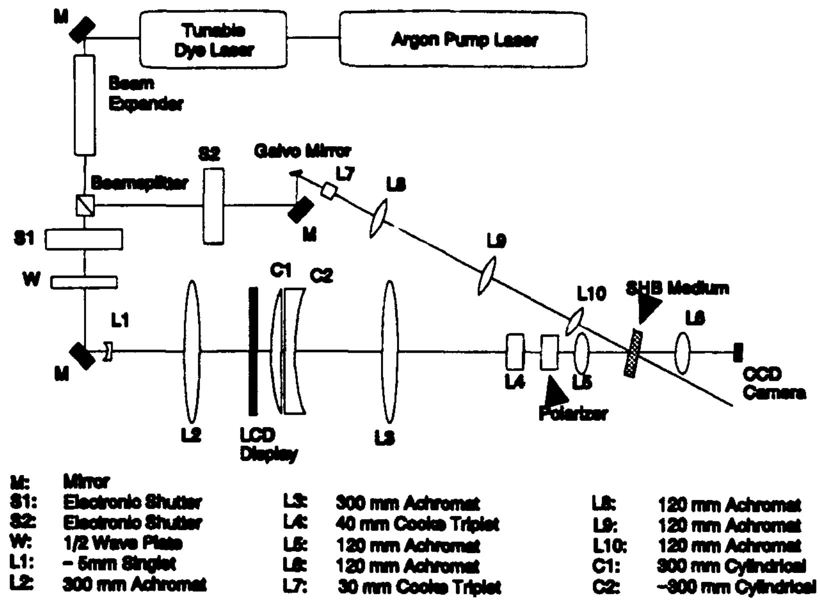

Figure 4. Schematic drawing of the optical system of our 4D computer memory system

by introducing two cylindrical lenses just after the LCD. These elements should alter the aspect ratio as desired while adding only a small and acceptable amount of astigmatism to the image.

The reference beam leg of the system is a simple relay optical system which projects a simple 1 cm diameter uniformly illuminated beam spot to the intersection point with the SHB medium (which is contained within the cryostat). The intersection angle is approximately 17 degrees and the plane of polarization for both beams is perpendicular to the plane of intersection. Angle multiplexing is carried out by use of a single galvanometer which is located at one end of the relay optics. Some magnification is introduced to provide very precise angular placement from the galvanometer and allow maximum repeatability even with relatively thick holographic media (which are very angularly selective).

2.9 System Control

Overall system control is provided by a simple 80286 based PC compatible. This system is of adequate speed and capability to provide the I/O control of all the system components. Standard interface cards provide communication to the shutters, motorized micrometers, the LCD system and the camera. This PC also does all the data encoding, decoding and error checking. For the specialized experiments associated with the frequency channels and erasure, this PC also has an A/D interface card added which enables efficient data recording and analysis. As with the rest of the system, all components are low cost and commercially available.

3 Frequency Channels & Erasure

The concepts behind our investigations of frequency channels have been discussed in detail previously [2] and summarized in the introduction to this report, therefore we shall not discuss them further here. Our principal experimental interest is to investigate their fundamental properties and obtain an early determination of the practicality of utilizing them in a mass storage system in the future.

The initial experiments which we are reporting on here (this work is continuing and will be properly discussed at the completion of the program) focus on determining the necessary conditions for the creation of frequency channels. We have also made an initial examination of the prospects for implementing a photoinduced erasure process in our memory system.

3.1 Frequency Channels

Our investigations of frequency channels must begin with a preliminary look at the properties of the SHB medium which we have selected because spectral hole burning in tetraphenyl chlorin doped polystyrene has not been previously reported. We begin by a simple measurement of the spectral characteristics of the primary absorption peak in the vicinity of 650 nm. Of particular interest was the observation of the spectral changes noted in Figure 5 upon cooling to 6 K. The spectral features of note are that the spectral peak shifted to a shorter wavelength by approximately 4 nm and increased in optical density by roughly 30 %. These changes are in qualitative agreement with observations reported by previous workers on other SHB media which are polymer based. We surmise that the frequency shift noted is largely due to an increase in the material density upon cooling which reduces the intermolecular spacings. The increase in optical density is probably related to a redistribution of the molecular populations of the absorbing species among the various energy states as the temperature is lowered.

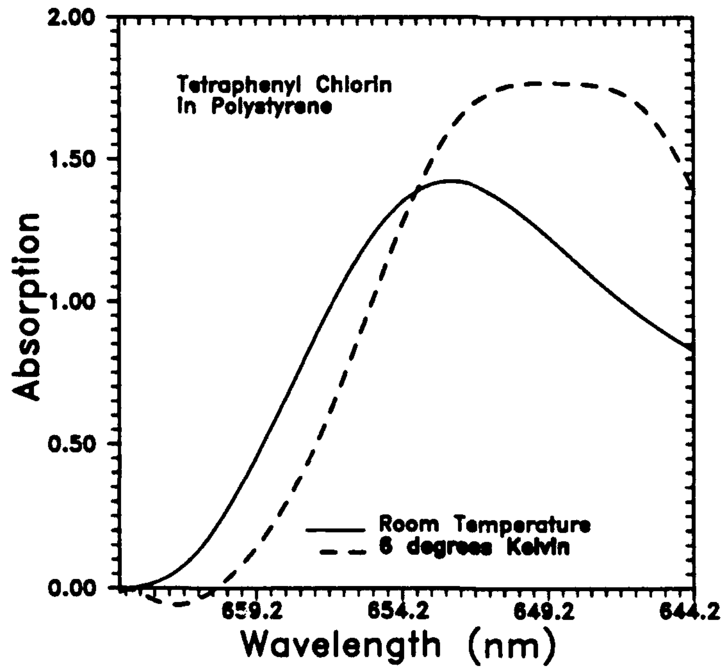

Figure 5. Absorption spectrum shift noted upon cooling of the SHB medium to 6K.

The next characteristic of interest is the dynamics associated with creating spectral holes. For these experiments we simply carry out exposures of the SHB medium at a fixed laser frequency and then measure the transmission as the tunable laser wavelength is swept across a small frequency range. As was discussed in a previous section, the dye laser used has a linewidth of roughly 2.5 GHz. Most of the polystyrene based SHB media generally exhibit a fundamental homogeneous line width of 1 to 2 GHz virtually independent of the dopant species (at 4K). Even for an infinitely narrow laser linewidth, the actual measured hole width is always twice that of the fundamental hole width. When the issue of our laser line width being comparable in magnitude to the hole width is factored in we would anticipate that the observable hole width should be approximately 4.5 to 6.5 GHz. This was indeed very close to the observed hole width of approximately 7 GHz (see Figure 6) which matches our prediction, within our measurement error.

As is typical for SHB experiments, this narrow spectral hole width was obtained at the lowest exposure power level, less that 100 μwatts. While this low power level exposure provides the greatest isolation of information as a function of frequency, it forces us to be impractically slow. Increasing the exposure by roughly a factor of 10 causes a small, but quite acceptable increase in the hole width, as is shown in Figure 7. A further increase in the exposing power level causes a noticeable increase in the spectral hole width but without any real increase in the hole depth as is seen in Figure 8. This suggests that this last increase in the power is now contributing to a significant temperature rise within the material. Because the SHB sample used is roughly 2.5 mm thick the thermal conductivity of the sample at these low temperatures is limiting the ability of the sample to retain its spectral selectivity. (As has been discussed in an earlier report [2] this is not a long term problem, but is important for us to note for the design of our experiments here.)

Another key observation is that the total dose at the highest power level was also larger, but the hole depth was not noticeably improved. This suggests that the spectral distribution of the photobleached molecules is no longer a simple lorentzian shaped spectral hole but is more complex. It is clear, that the best experimental results can only be obtained by careful attention to the exposure power level when thick samples are used. For the 2.5 mm thick sample used here a 1 mW exposure level seems optical.

Raising the temperature of the medium typically widens the spectral hole, as is observed in Figure 9. We carried out our exposures at two power levels and again observed the hole width. The fact that the hole width at the highest power level is roughly independent of temperature (compare with the previous figure) supports our contention that the sample is being overheated by the laser illumination at this highest power level.

Having briefly examined the basic characteristics of the SHB medium, we then initiated an early examination of the procedures required for the creation of frequency channels. We realized that the use of power levels higher than 1 mW/cm^2 would not be optimal, but our intent was to obtain an early examination of the desired frequency channel structure. To carry this out, we caused the laser wavelength to scan continuously across the central portion of the absorption peak. During the scan, the electronic shutter was periodically opened and closed. This exposure required approximately 20 minutes.

After the exposure was complete a transmission spectrum was measured and is shown in Figure 11. This figure clearly exhibits the basic elements of the frequency channel structure which has been anticipated. Absorption channels which have been bleached to an optical depth

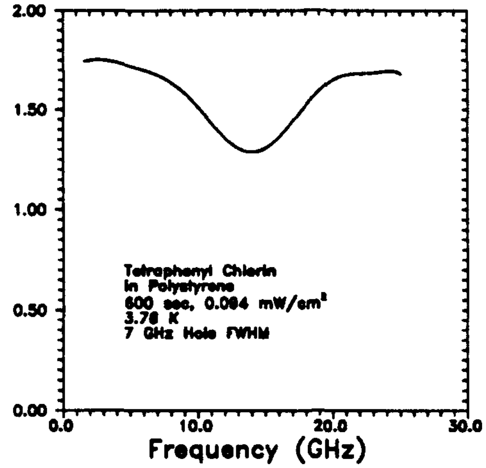

Figure 6. Spectral hole created at very low power illumination.

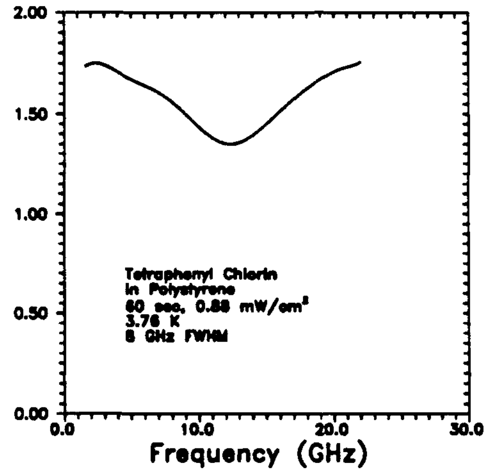

Figure 7. Spectral hole created at moderate power illumination. Note that the hole width has only increased slightly.

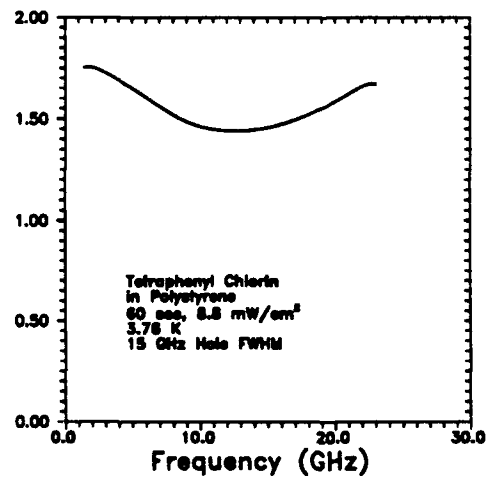

Figure 8. Spectral hole created at high power levels. Note that the hole width has increased substantially and that the hole depth has not increased despite the increased total dose.

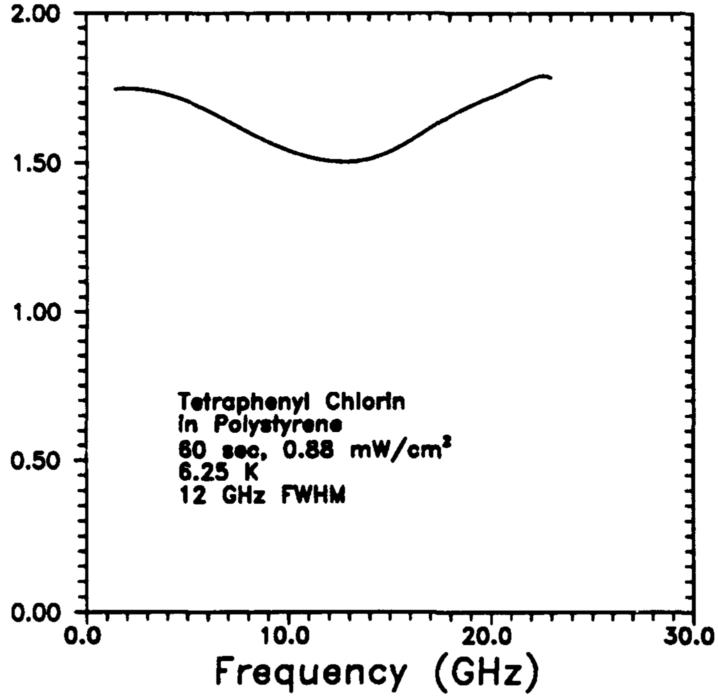

Figure 9. Spectral hole created at moderate power levels and a somewhat higher temperature. Note the increase in spectral hole width with temperature.

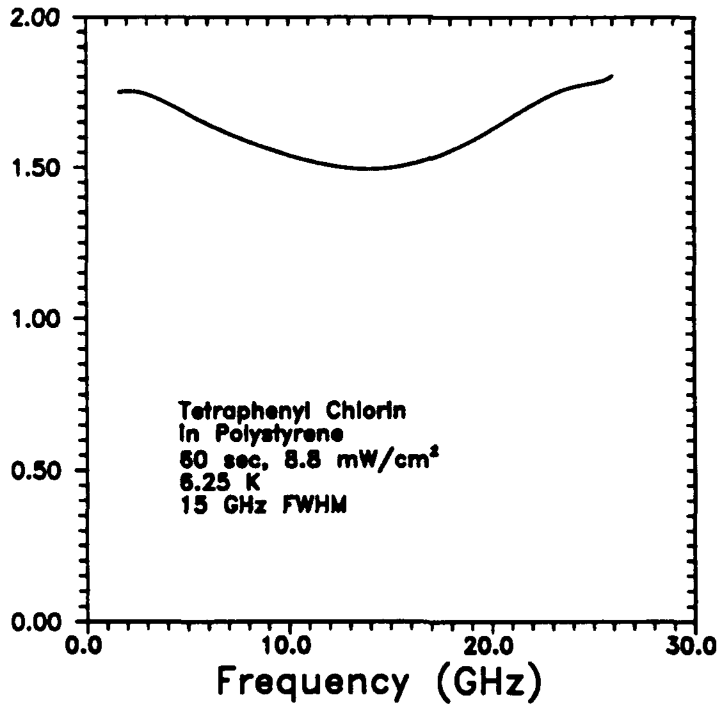

Figure 10. Spectral hole created at high power levels and the higher temperature. The hole width would appear to be principally determined by the power level of the laser illumination.

of roughly 25% of the total absorption peak are clearly observed. Within the resolution of this early measurement, the edges of each channel are sharp and easily distinguished.

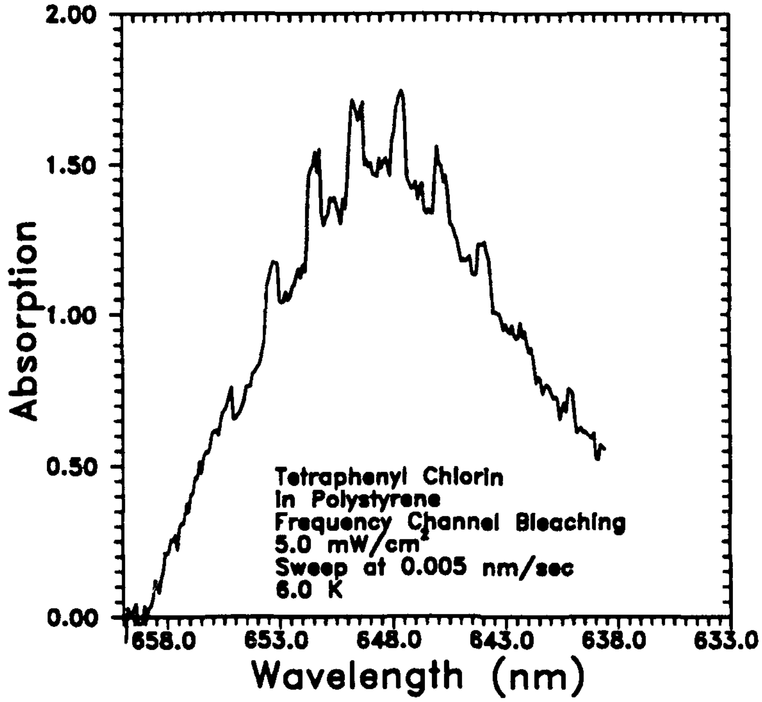

Figure 11. Frequency channel structure created by sweeping the laser wavelength across the absorption peak and intermittently opening the shutter.

To increase the optical depth of each channel, the exposure procedure was repeated and the result is seen in Figure 12. While the depth of each channel is noticeably increased, it is not doubled, a fact which may be related the the relatively high power level of 5 mW/cm^2 used for the exposures. Accompanying the increase in depth of the channels is an overall modest decline in the total height of the absorption peak. This was anticipated, because of the distributed spectral characteristics described by the Debeye-Waller factor. This has also been discussed in a previous report.[2] This factor describes the fact that the spectrum related to each spectral hole includes a component which is well distributed across the entire absorption peak. As many spectral holes are created the optical absorption in the spectral regions which were not exposed also declines.

One practical issue surrounding our required examination of the frequency channel structure is the requisite exposure time, not in future systems, but rather for these early experiments. At power levels less that 1 mW/cm^2, creating frequency channel structures throughout the entire absorption peak could requires days worth of exposure time. We therefore investigated the feasibility of reducing this exposure time substantially for our experimental purposes by effectively "slicing off" much of the absorption peak. How this was accomplished can be seen by reference to Figure 12. Here we see the Gaussian shaped absorption peak before exposure, and then immediately following a bleaching exposure which effectively cuts away a large segment of the peak. The shorter wavelength side of the peak is almost untouched, while the left side has

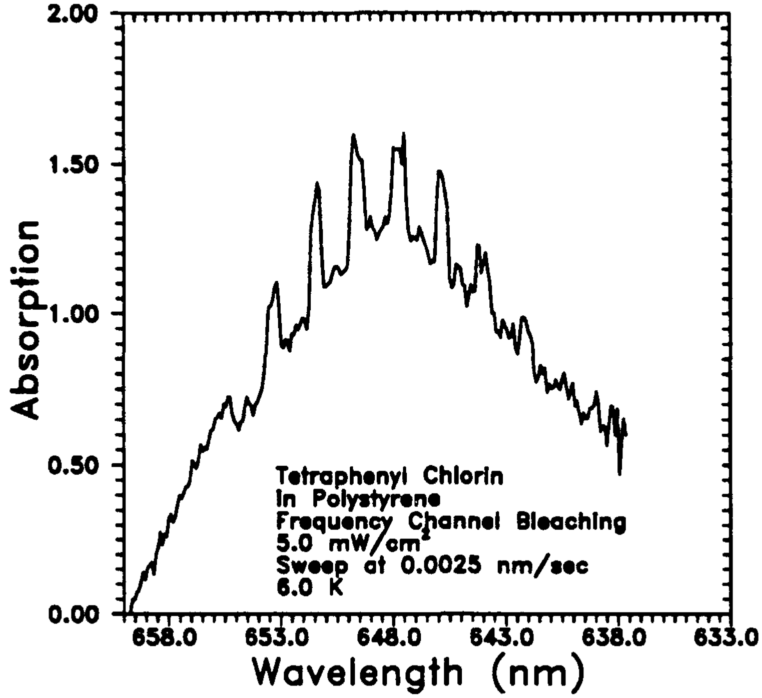

Figure 12. Frequency channels which are of greater depth were degenerated by further increasing the exposure time to the SHB medium.

been rounded and reduced in overall magnitude. This is caused by the spectral characteristics related to the Debeye-Waller Factor, and clearly demonstrates that it is asymmetric. The short wavelength absorption edge remains quite sharp at all exposure levels and shows the clear ability to provide the frequency selectivity.

This sharp edge is roughly half of the total absorption height and should provide an excellent frequency region in which to examine frequency channels. Channels created near this sharp edge should have the depth and quality we desire for our measurements.

These results are considered very encouraging, but still very preliminary. Now that it has been established that these requisite qualitative characteristics have been observed under these early experiment, our plans for the next segment of the work in this program are to quantitatively improve the sharpness and depth of these channels, and measure the characteristics of phase holograms recorded in these structures.

3.2 Erasure

We have also initiated our examination of photoinduced erasure. This was accomplished by simple sampling a small portion of the argon-ion laser beam which is used to pump the dye laser. With the wavelength being roughly 514 nm, it falls well into a higher spectral region of the TPC molecule. To test the effectiveness of utilizing this light source for erasure we illuminated the SHB medium immediately following our experiments with creating frequency channels. A 10 minute exposure at 3.5 mW/cm^2 was sufficient to completely erase the frequency channels which had been created by 40 minutes of exposure at 5 mW/cm^2 (see Figure 14). This indicates that the erasure process is at least 5 times more efficient that the hole burning process. This is a

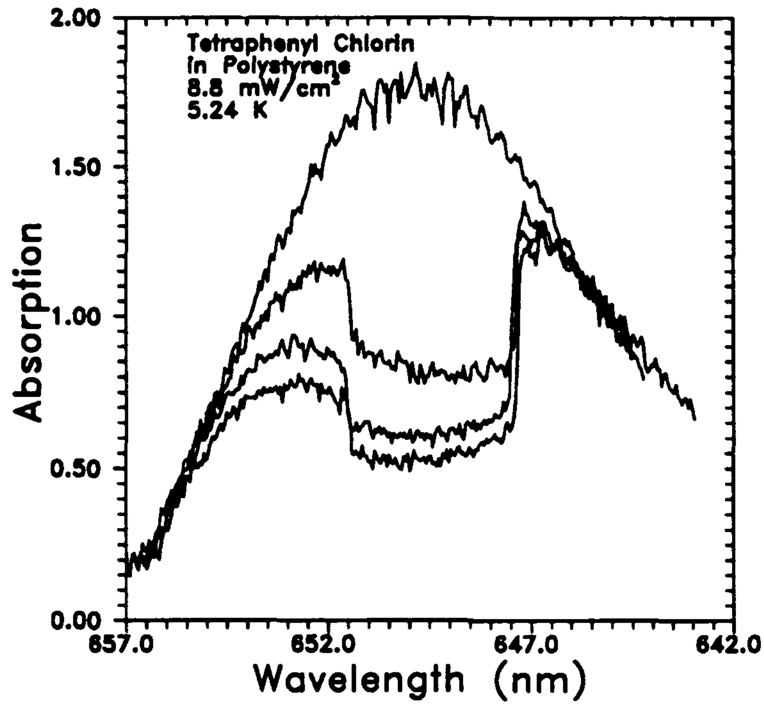

Figure 13. This experiment shows the effects of repeated bleaching exposures and how the Debeye-Waller factor plays a role. The initial absorption peak is shown in the top curve. After a wavelength sweeping exposure of 8.8 mW/cm^2 for 800 seconds we obtain the second curve. An additional 800 seconds produced the third curve, and another 800 second sweep provided the forth. Note the sharp absorption edge present at shorter wavelengths.

very desirable relationship. It indicates that erasure can be carried out very rapidly, but not so rapidly that the medium is overly sensitive to unintentional erasure by stray room light.

Continuing the exposures further caused the absorption peak at 650 nm to increase further, well beyond the original absorption obtained when the SHB medium is simply cooled from room temperature. This means that a substantial fraction of the TPC molecules are "spectrally frozen" in the higher energy absorption state and can be pushed into our favored absorption peak at 650 nm by exposure at 514 nm. The exposures which we have carried out so far have increased the optical absorption at 650 nm by approximately 50 %. Besides being important for the long term viability of a SHB medium to be easily erasable, this simple photoerasure process is also convenient for our experiments, permitting us to repeatedly expose and erase our medium while remaining cold and permitting us to carry our many experiments without warming the material between experiments (a time consuming process). Our plans are to further explore these processes now that we have determined the approximate experimental conditions required.

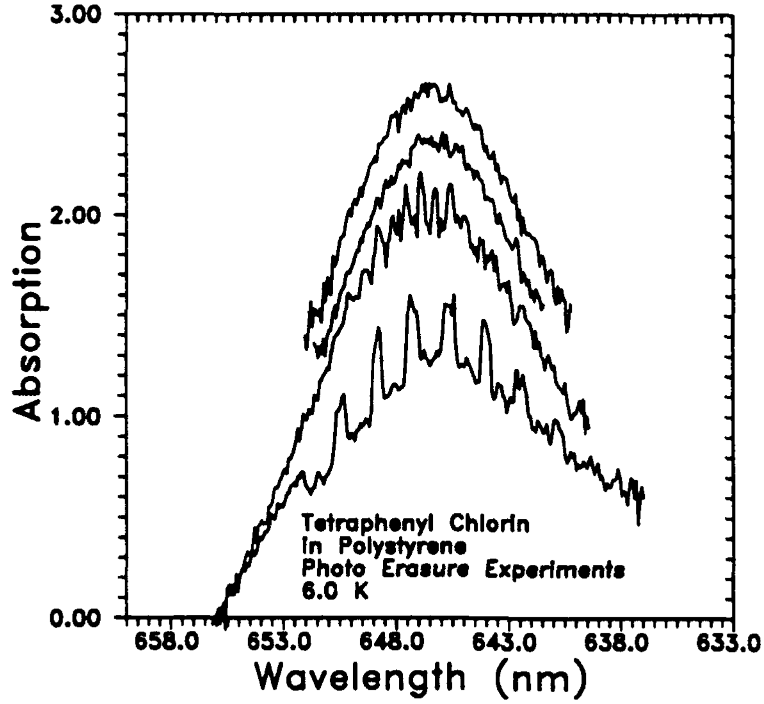

Figure 14. This figure shows how illumination with the 514 nm erasure beam completely wiped out the recorded frequency channel structure. The bottom curve was the initial channel structure created after 40 minutes of exposure. The next higher curve was measured after 10 minutes of exposure by the erasure beam (the fine structure present at the top of the peak is measurement noise and not a residue of the channel structure). The continuing exposure by the erasure beam continued to increase the absorption of the spectral peak.

4 Data Longevity

A key aspect of any memory system is the data life. A factor which we felt to be of initial key importance is the practical aspect of maintaining the recorded data in a holographic medium, at cryogenic temperatures, for prolonged periods.

To address this issue we enlisted the assistance of CTI Cryogenics Corp. of Mansfield MA. They provided us the usage of a Model 20 cryogenic refrigeration system for several months which can easily maintain an operating temperature of 8 K for long periods of time. The compact refrigeration head is suitably compact for usage in a high performance memory system, and the rated reliability of 20,000 hours is sufficient for most system applications.

This system provides refrigeration via thermal contact with end of the cold head, so thermal contact to our insulating polystyrene samples is a modest issue. This issue was addressed by fabricating a copper sample holder which can maintain a static helium atmosphere around the polystyrene sample. Sapphire windows permit laser illumination and hologram recording as well as excellent thermal conduction. The copper sample holder is mounted to the end of the cold head and cooled conductively. The helium atmosphere is supplied through stainless steel tubing which can be sealed off and carries very little heat load to the system. A standard vacuum shroud for the refrigerator head was obtained and evacuated while the system was being cooled. Once

the operating temperature was achieved, the vacuum pump was disconnected, since an adequate vacuum was easily maintained by the cryopumping induced by the cold head itself.

For these experiments, the holographic medium selected was Chlorin-I in polystyrene. Because the absorption peak of this material is 635 nm we could carry out our exposures with a simple HeNe laser. A simple Mach-Zender interferometer system set at approximately 20 degrees was assembled with an Air Force resolution target introduced on one leg to permit us to record a detailed holographic image. The hologram was recorded via a CCD camera and the image was stored in PC memory.

4.1 Experimental Results

Several experiments were carried out in order to determine the practical modes for operating this refrigeration system for holographic recording. We found that the vibrations introduced by the mechanical motions of the piston in the cold head were a severe problem. These vibrations prevented us from recording any reliable holograms while the system was turned on and actively cooling the SHB sample. Attempting to make mechanical contact to the cold head via a flexible copper filament did not seem to work either. This approach required that the sample holder be mounted rigidly to the optical bench while the copper filament make efficient thermal, but weak mechanical contact to the cold head. While this concept could probably have been made to work if engineered carefully, these early efforts were principally aimed at determining the effectiveness of our "easy solutions".

We found, in our experiments, that we could achieve efficient hologram recording if the refrigerator system were temporarily turned off. The system would warm to roughly 18 degrees in 2 minutes, providing us with adequate exposure time to record our high efficiency holograms. After exposure, the refrigerator could be turned on again and the temperature maintained indefinitely. For hologram readout, the vibration issue was not significant. Neither the image quality or hologram efficiency was significantly affected by the vibration problem under the conditions of our tests.

Two sets of longevity tests were performed. In the first, simple holographic gratings were recorded, and in the second, holographic images of the resolution target were recorded. The holographic gratings obtained had efficiencies as high as 1.5 % which we believe to be the highest recorded in an SHB medium. This also compares favorably with the maximum theoretical efficiency of 3.7 % for an absorption hologram. After recording the holographic diffraction efficiency was measured at various time intervals up to 100 hours and the slow exponential decay was recorded (see Figure 15).

In the second set of experiments holographic images of the resolution chart were recorded and observed with the CCD camera at various intervals. As in the above the exponential decay of the hologram strength was tracked, this time for a period of over two weeks. Over this time period, the hologram remained observable although the noise due to scatter from the SHB sample surfaces and microbubbles became a significant issue as the hologram efficiency declined. From the hologram efficiency data shown in Figure 15 one notes that there appeared to be a non-exponential decline in the hologram efficiency. We quickly traced this problem to slight mechanical instability of the optical mounts used in our experimental system. (Realistically speaking, we had not expected to carry on the experiment as long as we did.) We believe that with a somewhat more rigidly designed mechanical system, the efficiency decline would have

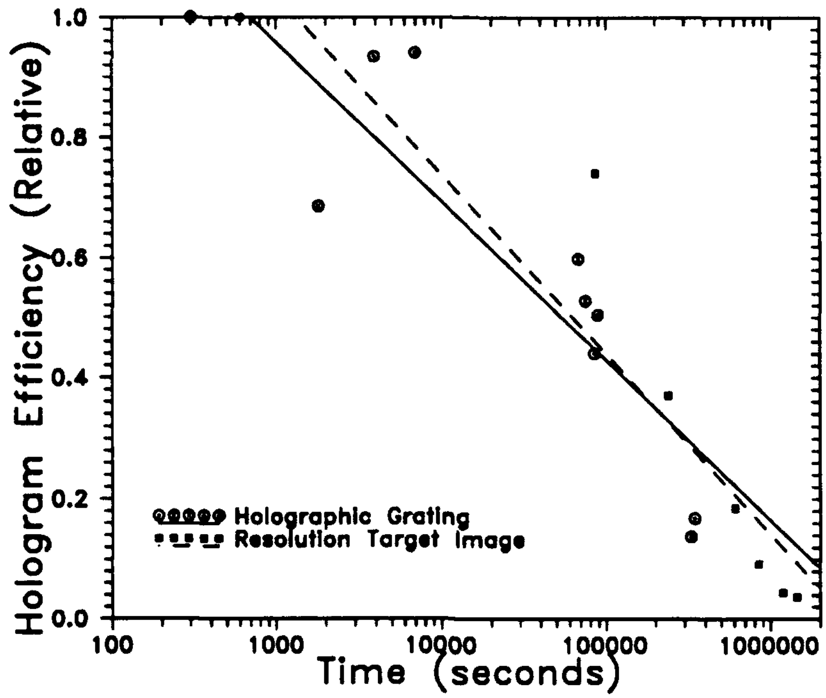

Figure 15. Diffraction efficiency measurements over a period of two weeks for a hologram recorded in chlorin-doped polystyrene. The use of a deuterated polymer host should improve the lifetime by several orders of magnitude.

remained simply exponential. From the images observed in Figures 16 to 22 one can see that the holographic image quality obtained was good and matched that obtained by us using a liquid helium cryostat at 5 degrees K. This sequence of images represents the images observed for periods up to 17 days after the initial hologram recording

4.2 Conclusions

These experimental results lead us to several important conclusions.

1) A cryogenic refrigeration system is quite compatible with the cooling requirements for a SHB based memory system. The refrigeration reliability was excellent and an ambient temperature of 8 K could be maintained indefinitely. We did observe that when modest exclusions in the temperature were permitted (as much as 10 degrees), there were no lasting effects noted in terms of data decay or loss of hologram efficiency. The system we used had an air cooled compressor which seemed to permit some sensitivity to the room air temperature (i.e. the cold head temperature would rise as the room temperature increased). However, this could be easily controlled with proper room ventilation.
2) The use of a simple helium filled sample holder with transparent windows provided quite a suitable vacuum tight yet thermally conductive arrangement for maintaining the required environment around the SHB medium. Our design is simple, compact, appears to be suitably reliable and allows us to maintain the helium atmosphere in a cryogenic

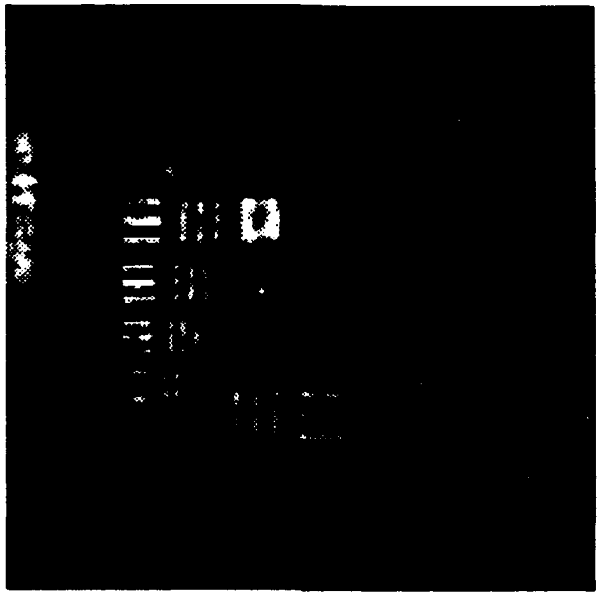

Figure 16. CCD camera image of the initially recorded resolution chart.

Figure 17. Holographic image recalled immediately following recording.

Figure 18. Holographic image recalled 3 days after the initial recording.

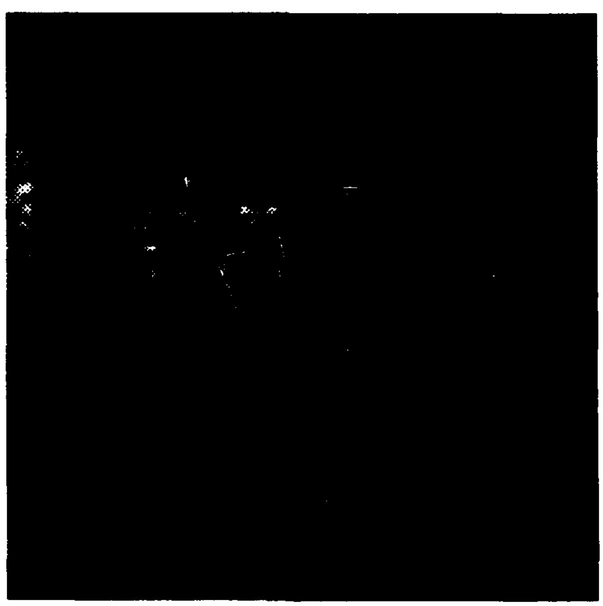

Figure 19. Holographic image recalled 7 days after the initial recording.

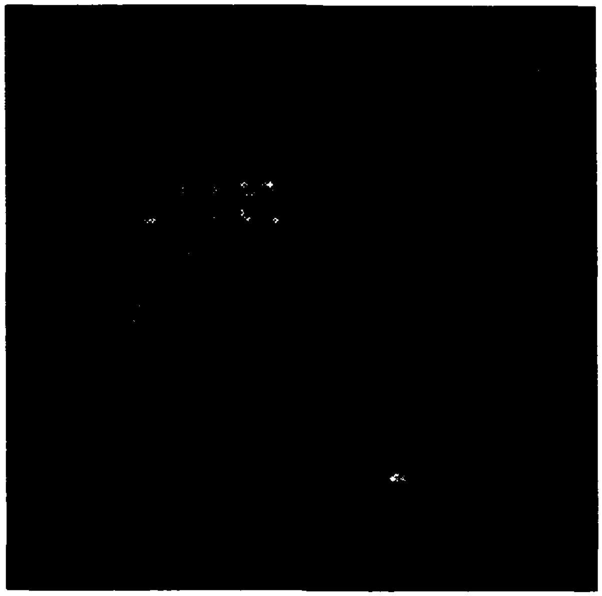

Figure 20. Holographic image recalled 10 days after the initial recording.

Figure 21. Holographic image recalled 14 days after the initial recording.

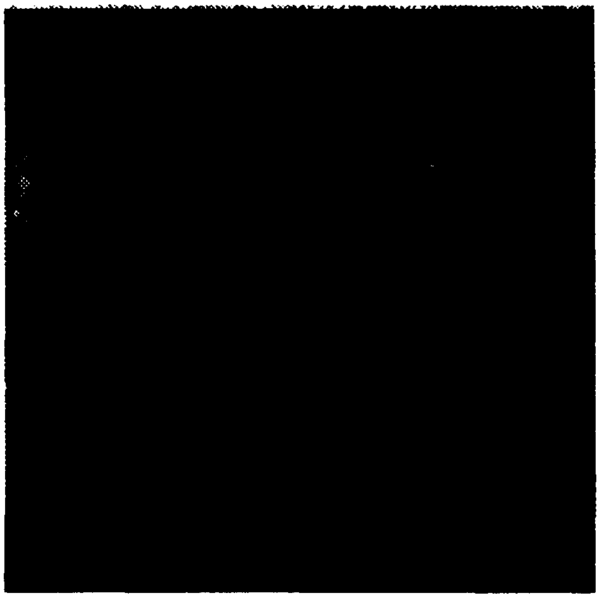

Figure 22. Holographic image recalled 17 days after the initial recording. While barely readable, the image is clearly present and principally masked by the scattering due to defects in the polystyrene host medium.

vacuum environment for prolonged periods. This design concept permits us to utilize refrigerators which require samples to be cold finger mounted.

3) The vacuum shroud used was a commercially available assembly which we believe had only a limited vacuum integrity, however it maintained a suitable quality vacuum for a period of two weeks. We believe that a properly sealed shroud design could be implemented in the future which would permit a permanent high integrity vacuum seal.
4) The vibration issue is a significant one but we are convinced that straightforward engineering solutions exist. An example of such a solution is a vacuum shroud design available from Janis Research which is known as the "Model CS22-EXOL-2 Vibration Isolation Refrigerator". This device permits an optical sample to be coupled thermally to the cold head via an ambient helium atmosphere without any mechanical contact. The static helium pressure can be kept low to avoid turbulence effects and complete vibration isolation is achieved using a vacuum baffle arrangement. We hope to test such a system in future development programs.
5) The data longevity experiments were carried on for periods exceeding one million seconds. This indicates that the longevity issue can be addressed from both the fundamental and practical points of view. Fundamentally, this data life was suitable for many applications, however it has been shown by previous workers in the field of spectral hole burning to be easily addressed by the used of deuterated host media. This change has been shown to extend the observed life of the recorded data to periods extrapolated to 20,000 years. From the practical standpoint, our direct experience is that the existing refrigeration technology is adequate to provide the media cooling under the required optical readout conditions for extended periods of time. In particular, we found the CTI Cryogenics system to be compact, reliable and simple to use.

5 Concept for a Content Addressable Memory

During the course of this experimental work we have conceived of an approach which permits us to create a memory system which in which the recorded information can be retrieved associatively. Because SHB media store information as a function of wavelength, the readout becomes especially facilitated by broad band illumination. This permits direct access to all the stored information in parallel. It is our belief that such a system could provide extremely rapid search capabilities as well as double as a high performance memory system. We have applied for a patent of this concept.

Figure 23 shows a drawing of a CAM concept which uses holographic storage in SHB materials. A tunable laser, divided into two paths by a beamsplitter, illuminates a spatial light modulator and a beam deflector. A two-dimensional array of bits modulates the data beam, which is then Fourier transformed by a lens. A beam deflector followed by relay optics insures intersection of the reference beam with the data beam inside the SHB recording medium. The spatial light modulator is reimaged onto a detector array; the data retrieved from the memory are read out by this array when a reference beam of the proper wavelength and direction illuminates the SHB medium. A second detector array detects the Fourier transform of the reference beam (i.e., a point). This array, in combination with the diffraction grating in this beam path, determines the address of pages containing the search string. The broadband source is used to illuminate the recording medium simultaneously with all wavelengths, to perform a search of the entire memory with a single illumination pulse.

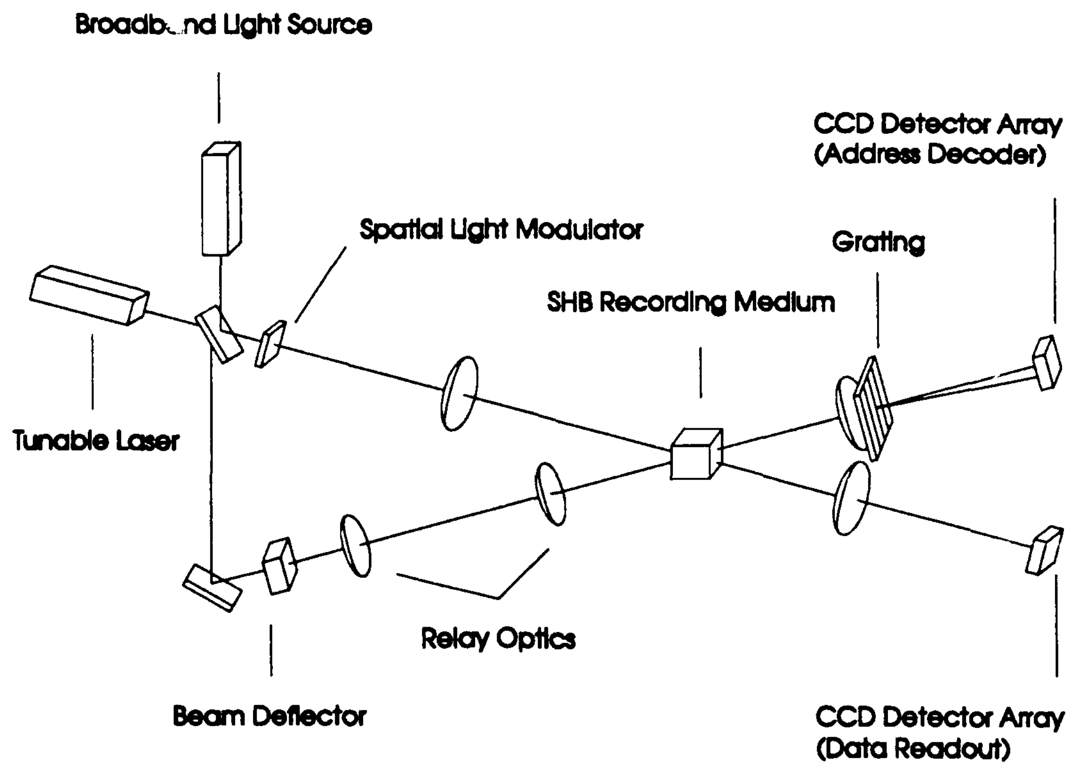

Figure 23. Schematic drawing showing the key components of a content addressable memory implemented using volume holographic storage in spectral hole burning materials.

Figure 24 illustrates, on a single page, all the important concepts which govern operation of our content addressable memory (CAM). The pairs of images on the left hand side of the page illustrate various pairs of inputs and outputs to and from the CAM. The comments on the right explain the significance of each example.

The top example shows an input data plane on the left and a reference beam on the right used to record a hologram in a 4D recording medium. The recording geometry is shown on the right, with the Input, Reference, Output 1, and Output 2 planes labeled. During recording of the original data, an entire input plane of data and a reference beam of a specific wavelength and Bragg angle (indicated by the x-position of the reference source) are projected simultaneously into the recording medium. The data plane shown in example 1 contains a vertical dash-dot-dash pattern to represent the search string to be located during CAM operation. Once the data have been recorded, the original reference beam can be projected into the 4D recording medium to reconstruct the original data plane, which will appear at Output 1.

The second example illustrates a well-known associative property of holograms. If part of the original data is projected into the hologram, an image of the original reference beam will be diffracted to Output 2. This experiment has previously been performed using a 2D hologram recording medium.[3,4] In the 2D case, the search pattern can be presented anywhere in the input plane. Because hologram recording and playback with a 2D medium are shift invariant, an output spot with a corresponding shift will be produced. When volume (3D) holograms are used, however, only certain shifts of the input are allowed. Shifts in the x-direction (as shown in example 3) correspond to changes in the Bragg angle, and do not produce a diffracted beam. Shifts in the y-direction, however, satisfy the Bragg condition, and produce a shifted output, as shown in example 4. Finally, because of the frequency-selective nature of the 4D recording medium, if the data are projected into a 4D hologram at the wrong wavelength, *no output will* be observed, as shown by example 5.

Once these properties of holograms recorded in 4D media are understood, we can show how simultaneous interrogation of the entire memory for a search string can be accomplished. In example 6, the search string is presented simultaneously at every input column and at every wavelength. This guarantees that the Bragg condition will be satisfied, and that holograms recorded at every wavelength will be interrogated. If the search string is present in the memory, a correlation peak will be diffracted into Output 2 at the same angular position as the correlation peak shown in example 2, in other words, in a position which corresponds to the original reference beam angle. This correlation peak will be at the original recording wavelength, however, since our detector array does not distinguish colors, we need a way to determine the wavelength address of the correlation peak. One possible method is shown in the bottom right of the page, opposite example 7. In this method, a grating is placed in the path to Output 2. The zeroth and first orders of light diffracted by the grating are incident on the detector array placed at Output 2, and the wavelength of the diffracted correlation peak can be determined from the separation of the two spots.

Architecture issues to be addressed analytically and experimentally include crosstalk between holograms as a function of spacing in reference beam angle and wavelength, hologram efficiency, storage capacity, and address finder operation. Previous work has shown that suppression of crosstalk is very important for achieving high signal to noise ratios in holographic memories.[5] Crosstalk may be caused by incomplete Bragg selectivity or by the width of the index of refraction effects in SHB materials, which is larger than the width of the homogeneous linewidth. The

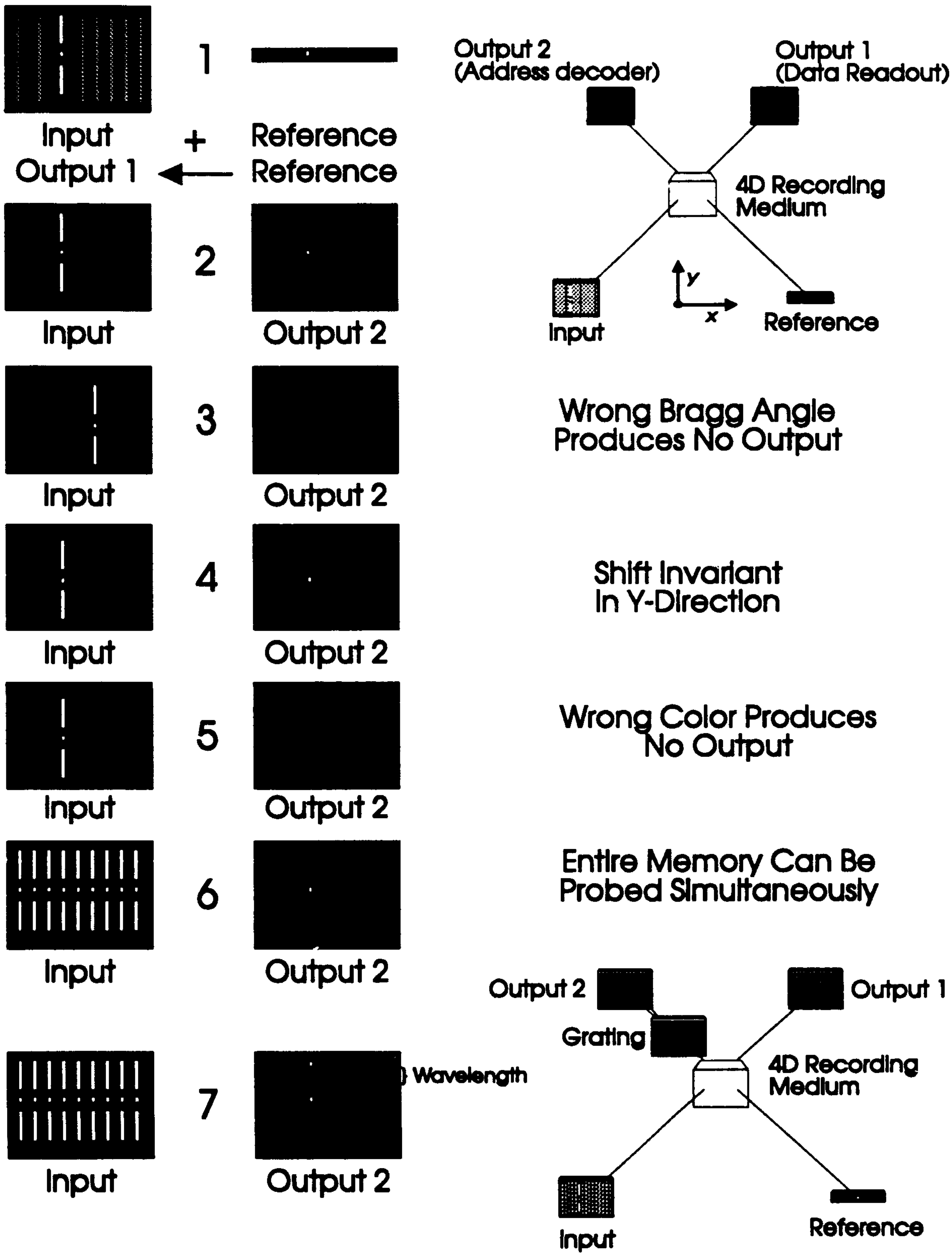

Figure 24. Schematic illustration of the principles of Content Addressable Memory operation.

number of holograms that can be multiplexed at any Bragg angle is limited by the diffraction efficiency required for each hologram. Multiplexing M holograms will reduce the efficiency of each hologram by $1/M^2$. The storage capacity will be determined by the total number of different page address combinations, while effective CAM operation requires that the address space be mapped onto a two-dimensional detector array. Figure 25 shows a possible arrangement of page addresses in Bragg and wavelength space which addresses these issues.

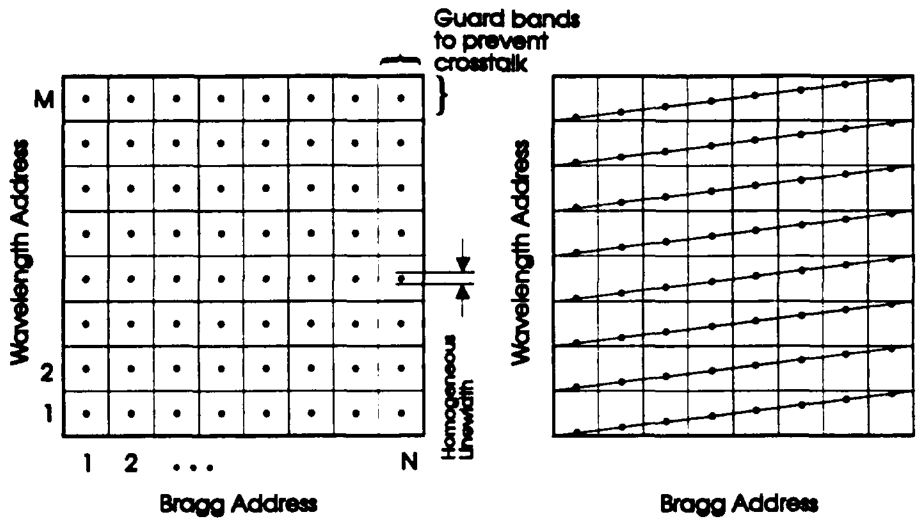

Figure 25. A rectangular array of page address in wavelength and Bragg space may not provide the best use of SHB materials. The rectangular array will multiplex N holograms in each narrow wavelength band. By tilting the array of addresses, as shown on the right, only one (or a small number) of holograms is written in each homogeneous linewidth.

5.1 Phase Coding for Address Finder Enhancement

In this section, we discuss how the error correction techniques we are using to improve the performance of our holographic optical memory provide the opportunity to improve CAM performance. These error correcting techniques provide improved bit error rate, and in addition allow us to implement "don't care" patterns to increase the flexibility of searches which can be performed directly in hardware using our CAM system.

Even with good signal to noise in a holographic memory, error correction techniques are needed to provide the performance required for a computer memory system. Patel has provided an in-depth discussion of signal and error control coding, which also contains many references to methods currently in use.[6] The error correction techniques we are using in our holographic memory system, combined with a new technique, phase coding, provide significant advantages for CAM.

The difference between error correcting codes (ECC) and error correcting modulation (ECM) has been discussed by Howe, *et al.*[7] ECC works to reduce the bit error rate (BER) by coding groups of bits, with additional (or redundant) bits used to provide error correction and detection. ECM corrects errors at their source by using signal patterns with characteristics that are well-suited to the recording medium. Magnetic recording has used both kinds of error correction to

achieve higher and higher recording densities. In the past, the limiting factor on the use of ECC was not the overhead of the extra bits required, but instead the hardware cost of the coding and decoding equipment. As the cost of the coding and decoding equipment drops, magnetic systems are tending to work with higher raw BERs and more ECC to achieve higher density storage. A rule of thumb for ECC performance is that an improvement of seven orders of magnitude can be achieved with an overhead of approximately 30%.

Holographic optical data storage is subject to many of the same degradations as magnetic and optical disk data storage. The two-dimensional nature of the output of a holographic system does not present a fundamental problem, because existing error correction systems have been designed to deal with both correlated (bunched) and uncorrelated (single) errors. We conclude that existing techniques and hardware are applicable to holographic memory systems. Of course, the type of error correction employed should be related to the types of errors that are most likely to occur in a given system.

Variable signal strength is a recognized problem for holographic memory systems, in part, because of erasure during subsequent recording and readout operations. (The use of spectral hole burning reduces this effect by a factor equal to the number of wavelengths used.) The effects of variable signal strength can be eliminated to a large degree using ECM in the form of slope detection. In this method, a zero bit can be encoded as a positive slope and a one bit can be encoded as a negative slope. Using a CCD detector array, each data value requires two pixels, resulting in 100% overhead, however, the reduction in error rate that can be achieved with this scheme followed by ECC may exceed the reduction that can be obtained using ECC alone. Slope coding has a key advantage important for holographic memory systems: the transmission of every bit plane is equal to 50%. This known, fixed value allows us to choose a reference beam of the proper intensity to prevent non-linear data recording, independent of the particular data pattern being recorded.

Slope coding has an advantage specific to CAM; the "on" pixels associated with every bit allow the use of phase coding. One effect of phase coding is to spread the energy from the data plane uniformly throughout the hologram medium, eliminating "hot spots" and improving the signal to noise for hologram recording. In addition, phase coding can sharpen the autocorrelation peaks and reduce the height of unwanted cross-correlation peaks. Figure 26 shows how phase coding works to achieve this effect. (This figure shows the electrical field strength of the sidelobes; the actual correlation intensities are the square of the electric field.) This figure illustrates two key results: without phase coding, the sidelobes build up nearly to the height of the autocorrelation peak, and cross-correlation peaks can be nearly as large as the desired autocorrelation peak, especially for cases such as shown here that differ only by one bit. In the phase-coded case, the sidelobes are nearly cancelled, and the signal to noise (ratio of peak to sidelobe intensity) will increase as the search sequence is lengthened.

In database operations, a search is often performed for a string with "don't care" bits or bytes, in which any character is acceptable. This capability can be provided by a special character when slope coding is used. This special character is composed of two "off" pixels, a combination which is not used to represent either a zero or one bit. This pattern has the advantage of introducing no light into the system, and thus it will neither add to or subtract from any correlation peaks indicating the presence of the search string. Since upper and lower case ASCII characters differ in only one bit position, a don't care bit will be extremely useful for performing case independent searches. When only a single pixel is used to represent each bit, three different levels of pixel

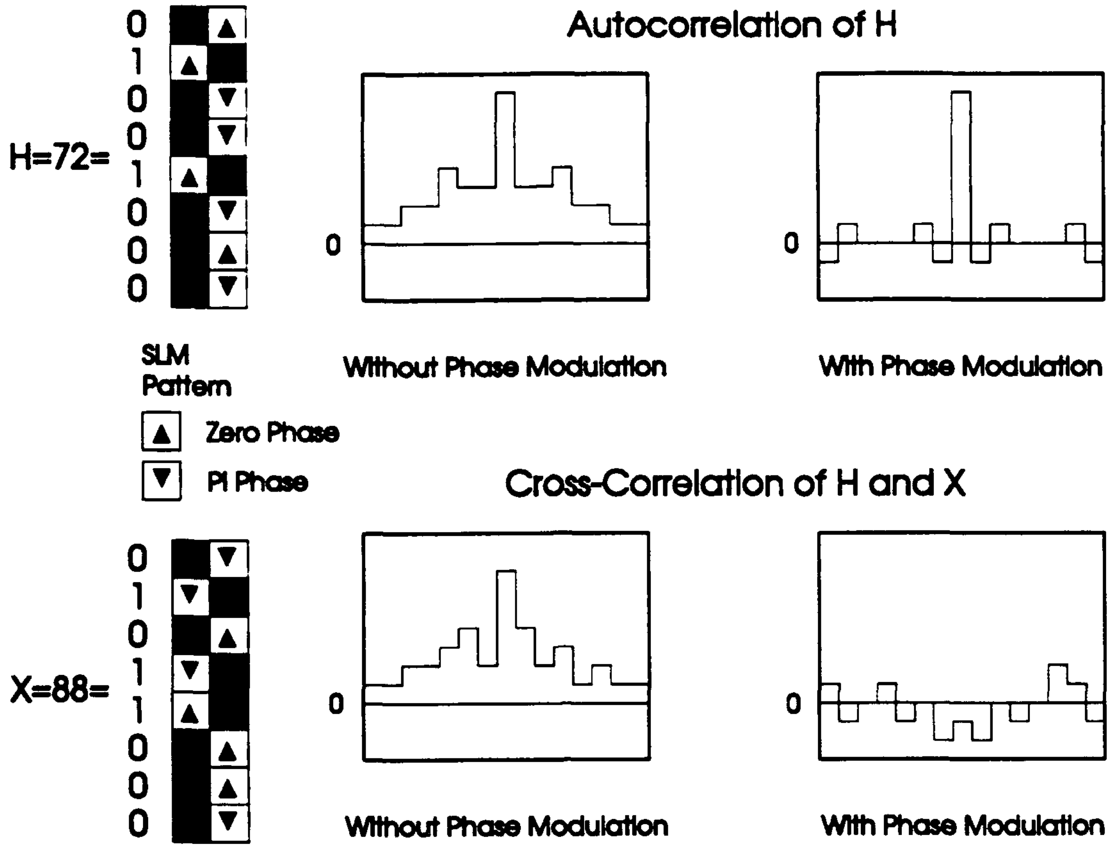

Figure 26. Illustration of the use of phase coding for suppression of sidelobes and cross-correlation peaks. (The examples show optical field strength.)

value must be distinguished to implement don't care bits, requiring a much higher signal to noise ratio for reliable operation. Thus, slope coding provides an important practical advantage for searching content addressable memories.

The combination of slope coding and phase coding requires simultaneous amplitude and phase modulation. This dual mode modulation can be achieved easily with liquid crystal spatial light modulators.[8] Figure 27 shows how a liquid crystal spatial light modulator with gray scale capability can be modified to produce dark pixels, or light pixels with a zero or π phase shift.

Phase code selection will determine a phase value of zero or π for each "on" state. Since every bit has an "on" pixel when using slope coding, a look-up table can define which of the two states is used for each bit in the ASCII representation of each character. Theory indicates a random phase code selection will be appropriate (since the order of ASCII characters in typical data will be nearly random).

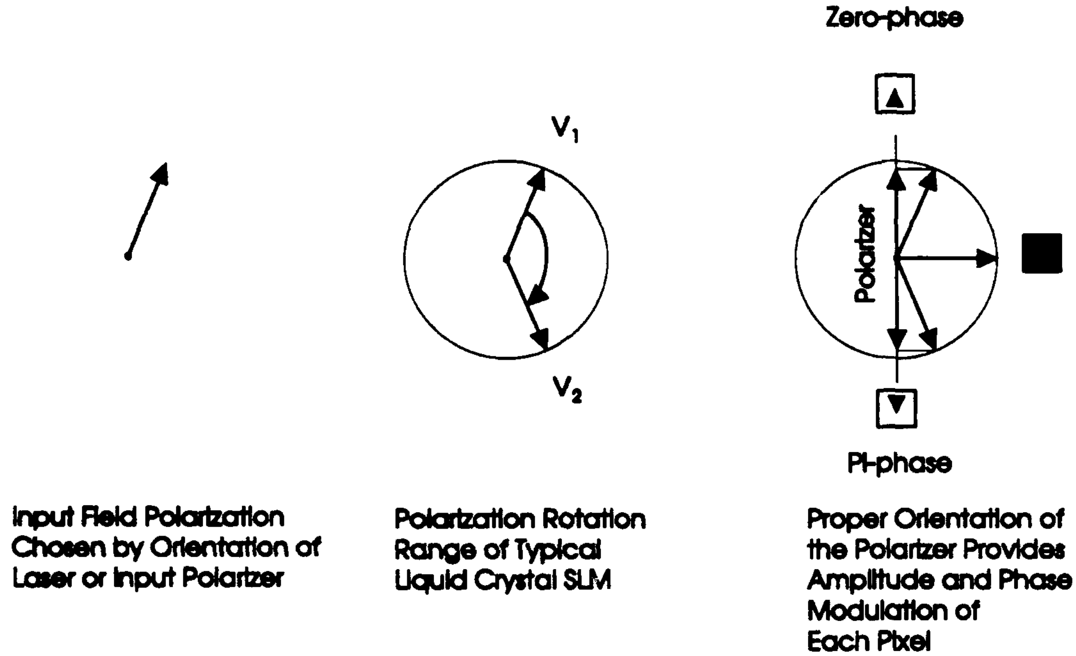

Figure 27. Reorientation of the polarizer associated with a liquid crystal SLM can produce dark pixels or bright pixels with zero or π phase shift.

6 Summary

The work on this program continues to progress well. At this time most of the major technical tasks have been only partially completed, with much of the effort so far being focused on preparation for the experiments. The results so far indicate that all the concepts which have motivated this experimental program are qualitatively correct, and only the continued quantitative analysis will provide the proper characterization needed.